Photometry of SN 2002ic and Implications for the Progenitor Mass-Loss History

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ABSTRACT

We present new pre-maximum and late-time optical photometry of the Type Ia/IIn supernova 2002ic. These observations are combined with the published V-band magnitudes of Hamuy et al. (2003) and the VLT spectrophotometry of Wang et al. (2004) to construct the most extensive light curve to date of this unusual supernova. The observed flux at late time is significantly higher relative to the flux at maximum than that of any other observed Type Ia supernova and continues to fade very slowly a year after explosion. Our analysis of the light curve suggests that a non-Type Ia supernova component becomes prominent ~ 20 days after explosion. Modeling of the non-Type Ia supernova component as heating from the shock interaction of the supernova ejecta with pre-existing circumstellar material suggests the presence of a $\sim 1.7 \times 10^{15}$ cm gap or trough between the progenitor system and the surrounding circumstellar material. This gap could be due to significantly lower mass-loss $\sim 15\ (\frac{v_w}{10\ \mathrm{km/s}})^{-1}$ years prior to explosion or evacuation of the circumstellar material by a low-density fast wind. The latter is consistent with observed properties of proto-planetary nebulae and with models of white-dwarf + asymptotic giant branch star progenitor systems with the asymptotic giant branch star in the proto-planetary nebula phase.

Subject headings: stars: winds — supernovae — supernovae: individual (2002ic)

1. Introduction

Historically, the fundamental division of supernova (SN) types was defined by the absence (Type I) or presence (Type II) of hydrogen in the observed spectrum. Later refinements distinguished Type Ia supernovae from other types of supernovae by the presence of strong silicon

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absorption features in their spectra (Wheeler & Harkness 1990; Filippenko 1997). Type Ia supernovae (SNe Ia) are generally accepted to result from the thermonuclear burning of a white dwarf in a binary system, whereas all the other types of supernovae are believed to be produced by the collapse of the stellar core, an event which leads to the formation of a neutron star or black hole.

While interaction with circumstellar material (CSM) has been observed for many core-collapse supernovae, the search for evidence of CSM around Type Ia SNe has so far been unsuccessful. Cumming et al. (1996) reported high resolution spectra of SN 1994D and found an upper limit for the pre-explosion mass-loss rate of $\dot{M} \sim 1.5 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for an assumed wind speed of $v_w = 10$ km s^{-1}. However, they also note that this limit allows most of the expected range of mass-loss rates from symbiotic systems ($\frac{\dot{M}}{v_{10}} \lesssim 2 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$). On the other hand, the surprisingly strong high-velocity Ca II absorption and associated high degree of linear polarization observed in SN 2001el by Wang et al. (2003) and the high velocity features in SN 2003du by Gerardy et al. (2004) have led these authors to suggest that the high velocity Ca feature could be the result of the interaction between the supernova ejecta and a CSM disk. About 0.01 $M_\odot$ of material is required in the disk, and the spatial extent of the disk must be small to be consistent with the absence of narrow emission lines at around optical maximum (Cumming et al. 1996). Due to the strength of the Ca II feature in SN 2001el, Wang et al. (2003) speculated that the disk of SN 2001el may have been over-abundant in Ca II. In contrast, Gerardy et al. (2004) found that a standard solar abundance of Ca II is sufficient to explain the observed feature in SN 2003du (Gerardy et al. 2004), for which the high-velocity Ca II feature is significantly weaker than in SN 2001el.

Supernova 2002ic (Wood-Vasey et al. 2002) is a very interesting event that shows both silicon absorption (Hamuy et al. 2002) and hydrogen emission (Hamuy et al. 2003). This SN is the first case for which there is unambiguous evidence of the existence of circumstellar matter around a SN Ia and is therefore of great importance to the understanding of the progenitor systems and explosion mechanisms of SNe Ia. By studying the spectral polarimetry and the light curve of the Hα line, Wang et al. (2004) found the spatial extent of the hydrogen-rich material to be as large as 10^{17} cm and distributed in a quite asymmetric configuration, most likely in the form of a flattened disk. The implied total mass of the hydrogen-rich CSM is a few solar masses. Similar conclusions were reached by Deng et al. (2004).

In this paper, we present new photometry of SN 2002ic and discuss the implications for the interaction of the ejecta and the CSM. Sec. 2 presents our data processing procedure and calibration for our photometry of SN 2002ic. In Sec. 3, we discuss the light curve of SN 2002ic and the immediate implications from our data. A more in-depth investigation and qualitative modeling of the light curve of SN 2002ic as an interaction of a SN Ia with surrounding CSM is presented in Sec. 5. Our discussion in Sec. 6 presents our interpretations of the structure of the CSM surrounding SN 2002ic. Finally, in Sec. 7 we present some intriguing possibilities for the progenitor system

of SN 2002ic and speculate on other possible SN 2002ic-like events.

2. Data Processing for SN 2002ic

2.1. Data processing and Discovery

We discovered SN 2002ic on images from the NEAT team (Pravdo et al. 1999) taken on the Samuel Oschin 1.2-m telescope on Mt. Palomar, California. In preparation for searching, the images were transmitted from the telescope to the High-Performance Storage System (HPSS) at the National Energy Research and Scientific Computer Center (NERSC) in Oakland, California via the HPWREN (Braun 2003)[1] and ESnet (U.S. Department of Energy 2004)[2] networks. These data were then automatically processed and reduced on the NERSC Parallel Distributed System Facility (PDSF) using software written at Lawrence Berkeley National Laboratory by WMWV and the Supernova Cosmology Project.

The first-level processing of the NEAT images involved decompression and conversion from the NEAT internal format used for transfer to the standard astronomical FITS format, subtraction of the dark current for these thermoelectrically cooled CCDs, and flat-fielding with sky flats constructed from a sample of the images from the same night. These processed images were then loaded into an image database, and archival copies were stored on HPSS. The images were further processed to remove the sky background. An object-finding algorithm was used to locate and classify the stars and galaxies in the fields. The stars were then matched and calibrated against the USNO A1.0 POSS-E catalog (Monet et al. 1996) to derive a magnitude zeropoint for each image. There were typically a few hundred USNO A1.0 stars in each 0.25 $\square^\circ$ image.

The supernova was discovered by subtracting PSF-matched historical NEAT images from new images, then automatically detecting residual sources for subsequent human inspection (see Wood-Vasey et al. (2004)).

2.2. Photometry

For analysis, we assembled all NEAT images, including later images kindly taken at our request by the NEAT team.

[1]http://hpwren.ucsd.edu

[2]http://www.es.net

Light curves were generated using aperture photometry scaled to the effective seeing of each image. A set of the 4 best-seeing ($< 3''$) reference images was selected from among all NEAT Palomar pre-explosion images from 2001 of SN 2002ic. Multiple reference images were chosen to better constrain any underlying galaxy flux. The differential flux in an aperture around SN 2002ic was measured between each reference image and every other image of SN 2002ic. Aperture correction was performed to account for the different seeing and pixel scales of the images. The overall flux ratio between each reference image and light-curve image was tracked and normalized with respect to a primary reference image. This primary reference image was chosen from the reference images used for the image subtraction on which SN 2002ic was originally discovered. The flux differences calculated relative to each reference were combined in a noise-weighted average for each image to yield an average flux for the image. As the observations were taken within a span of less than one hour on each night, the results from the images of a given night were averaged to produce a single light curve point for that night.

The reference zeropoint calculated for the primary reference image from the above USNO A1.0 POSS-E calibration was used to set the magnitudes for the rest of the measured fluxes. Table 1 reports these magnitudes and associated measurement uncertainties. An overall systematic uncertainty in the zeropoint calibration is not included in the listed errors. The USNO A1.0 POSS-E catalog suffers from systematic field-to-field errors of ~ 0.25 magnitudes in the northern hemisphere (Monet et al. 1996). The conversion of POSS-E magnitudes to V-band magnitudes for a SN Ia is relatively robust, as a SN Ia near maximum resembles a $\sim 10,000$ K blackbody quite similar to Vega in the wavelength range from $4,500$–$10,000$ Å. At late times, the observations of Wang et al. (2004) show that the smoothed spectrum of SN 2002ic tracks that of Vega red-ward of 5,000 Å. We estimate that, taken together, the calibration of our unfiltered observations with these POSS-E magnitudes and the subsequent comparison with V-band magnitudes are susceptible to a 0.4 magnitude systematic uncertainty. Any such systematic effect is constant for all data points and stems directly from the magnitude calibration of the primary reference.

However, the observed NEAT POSS-E magnitudes show agreement with the V-band magnitudes of Hamuy et al. (2003) and the V-band magnitudes obtained from integrating the spectrophotometry of Wang et al. (2004) to significantly better than any 0.4 magnitude systematic uncertainty estimate. This synthesized VLT photometry is presented in Table 2. Comparing the photometry of SN 2002ic and nearby reference star with a similar color ($B - R = 0.3$), we find agreement between the VLT V-band acquisition camera images and the NEAT images to within ± 0.05 magnitudes. Given this good agreement, it appears that our POSS-E-calibrated magnitudes for SN 2002ic can be used effectively as V-band photometry points.

Mario Hamuy was kind enough to share his BVI secondary standard stars from the field of SN 2002ic. We attempted to use these stars to calculate the color correction from our POSS-E mag-

nitudes to V-band, but our analysis predicted an adjustment of up to $+0.4$ magnitudes. This was inconsistent with the good agreement with the VLT magnitudes (calculated correction = $+0.1$ mag) at late times and with the Hamuy V-band points after maximum ($+0.4$ mag). This disagreement is not fully understood. We note, however, that the colors of the secondary standard stars did not extend far enough to the blue to cover the majority of the color range of the supernova during our observations (a common problem when observing hot objects such as supernovae). In addition, as there is no color information from before maximum light, it is possible that SN 2002ic does not follow the color evolution of a typical SN Ia.

Our newly reported pre-maximum photometry points (see Table 1 and Fig. 1) are invaluable for disentangling the SN and CSM components, which we now proceed to do.

3. Light Curve of SN 2002ic

The light curve of SN 2002ic is noticeably different from that of a normal SN Ia, as can be seen in Fig. 2, and as was first noted by Hamuy et al. (2003). The detection of hydrogen emission lines in the spectra of SN 2002ic in combination with the slow decay of the light curve is seen as evidence for interaction of the SN ejecta and radiation with a hydrogen-rich CSM (Hamuy et al. 2003; Wang et al. 2004). The profile of the hydrogen emission line and the flat light curves can be understood in the context of Type IIn supernovae as discussed in Chugai et al. (2002), Chugai & Yungelson (2004), and references therein.

The data presented here show that the slow decay has continued ~ 320 days after maximum at a rate of ~ 0.004 mag/day, a rate that is significantly slower than the 0.01 mag/day decay rate expected from Co^{56} decay (also see Deng et al. (2004)). In addition, our early-time points show that the light curve of SN 2002ic was consistent with a pure SN Ia early in its evolution. This implies that there was a significant time delay between the explosion and development of substantial radiation from the CSM interaction, possibly due to a a physical gap between the progenitor explosion and the beginning of the CSM. After maximum, we note the existence of a second bump in the light curve, which is put in clear relief by our photometry data on JD 2452628.6. We interpret this second bump as evidence for further structure in the CSM.

4. Decomposition of SN Ia and CSM components

Hamuy et al. (2003) performed a spectroscopic decomposition of the underlying supernova and ejecta-CSM interaction components. We perform here an analogous photometric decomposition. To decompose the observed light curve into the contributions from the SN material and the

shock-heated CSM, we first consider a range of light curve stretch values (Perlmutter et al. 1997), using the magnitude-stretch relation, $\Delta m = 1.18\,(1-s)$ (Knop et al. 2003), applied to the normal SN Ia template light curve of Goldhaber et al. (2001); we consider the remaining flux as being due to the SN eject-CSM interaction (see Fig. 2). At early times, the inferred contribution of the CSM is dependent on the stretch of the template chosen, but at later times the CSM component completely dominates for any value of the stretch parameter. It is not possible to disentangle the contribution of the CSM from that of the SN at maximum light, although a normal SN Ia at the redshift of SN 2002ic, $z = 0.0666$ (Hamuy et al. 2003), corresponding to a distance modulus of 37.44 for an $H_0 = 72$ km/s/Mpc (Freedman et al. 2001), would only generate about half of the flux observed for SN 2002ic at maximum. Hamuy et al. (2003) find that SN 2002ic resembles SN 1991T spectroscopically and note that SN 1991T/SN 1999aa-like events are brighter a month after maximum light than explainable by the standard stretch relation. A SN 1991T-like event (stretch$= 1.126$, $\Delta m = 0.15$, based on the template used in Knop et al. (2003) (A.J. Conley 2004, private communication)), would lie near the stretch$= 1$ line of Fig. 2. The light curve of SN 2002ic for the first 50 days is thus much too luminous to be due entirely to a 91T-like supernova. In addition, the spectroscopically-inferred CSM-interaction contribution of Hamuy et al. (2003) (open triangles in Fig. 2) limits the SN contribution at maximum to that expected from a normal SN Ia. After 50 days, SN 2002ic exhibits even more significant non-SN Ia-like behavior.

We next use the formalism of Chevalier & Fransson (1994) to fit a simple interacting SN ejecta-CSM model to the observed data. While Chevalier & Fransson (1994) focus on SNe II, their formalism is generally applicable to SNe ejecta interacting with a surrounding CSM. We simultaneously fit the SN Ia flux and the luminosity from the SN ejecta-CSM interaction. Our analysis allows us to infer the integrated radial density distribution of the CSM surrounding SN 2002ic.

5. Simple Scaling of the SN Ejecta-CSM Interaction

Following the hydrodynamic models of Chevalier & Fransson (1994), we assume a power-law supernova ejecta density of

$$\rho_{\rm SN} \propto t^{n-3} r^{-n} \tag{1}$$

where t is the time since explosion, r is the radius of the ejecta, and n is the power-law index of a radial fall-off in the ejecta density. Chevalier & Fransson (2001) note that for SNe Ia an exponential ejecta profile is perhaps preferred. However, this profile does not yield an analytical solution and so, for the moment, we proceed assuming a power-law profile. In Sec. 6 we explore the ramifications of an exponential ejecta profile.

Chevalier & Fransson (1994) give the time evolution of the shock-front radius, R_s, as

$$R_s = \left[\frac{2}{(n-3)(n-4)}\frac{4\pi v_w}{\dot{M}}A\right]^{1/(n-2)} t^{(n-3)/(n-2)}, \tag{2}$$

where v_w is the velocity of the pre-explosion stellar wind, $\dot{M}$ is the pre-explosion mass-loss rate, and A is a constant in the appropriate units for the given power-law index n.

Taking the parameters in the square brackets as fixed constants, we can calculate the shock velocity, v_s, as

$$v_s = \left[\frac{2}{(n-3)(n-4)}\frac{4\pi v_w}{\dot{M}}A\right]^{1/(n-2)} \left(\frac{n-3}{n-2}\right) t^{-1/(n-2)}. \tag{3}$$

Thus the shock velocity goes as

$$v_s \propto t^{-\alpha}, \tag{4}$$

where

$$\alpha = \frac{1}{n-2}. \tag{5}$$

We assume that the luminosity of the ejecta-CSM interaction is fed by the energy imparted at the shock front and view the unshocked wind as crossing the shock front with a velocity of $v_s + v_w \approx v_s$. As the wind particles cross the shock front, they are thermalized and their crossing kinetic energy, $\mathrm{K.E.} = \frac{1}{2}\rho_w v_s^2 dV$, is converted to thermal energy. Putting this in terms of the mass-loss rate, $\dot{M}$, we can express the CSM density as

$$\rho_w = \frac{\dot{M}}{4\pi R_s^2 v_w}, \tag{6}$$

and we can calculate the energy available to be converted to luminosity, L, as

$$L = \alpha(\lambda,t)\frac{d}{dt}\mathrm{K.E.} = \alpha(\lambda,t)\frac{1}{2}\frac{\dot{M}}{4\pi R_s^2 v_w}v_s^2 dV = \alpha(\lambda,t)\frac{1}{2}\frac{\dot{M}}{4\pi R_s^2 v_w}v_s^2 v_s 4\pi R_s^2. \tag{7}$$

The luminosity dependence on R_s drops out and we have

$$L = \alpha(\lambda,t)\frac{d}{dt}\mathrm{K.E.} = \alpha(\lambda,t)\frac{1}{2}\frac{\dot{M}}{v_w}v_s^3. \tag{8}$$

A key missing ingredient is a more detailed modeling of the kinetic energy to optical luminosity conversion term, $\alpha(\lambda,t)$. We note that the available kinetic energy is on the order of 1.6×10^{44} erg s^{-1} for $\dot{M} = 10^{-5}\ M_\odot$ yr^{-1}, $v_s = 10^4$ km s^{-1}, and $v_w = 10$ km s^{-1}. This implies a conversion efficiency from shock interaction K.E. to luminosity of 50%, given the luminosity, 1.6×10^{44} erg s^{-1}, of SN 2002ic and the typical luminosity of a SN Ia near maximum of

0.8×10^{44} erg s^{-1}. Assuming this constant conversion produces reasonable agreement with the data, so we proceed with this simple assumption. Using Eq. 4 to give the time dependence of v_s, we obtain the time dependence of the luminosity,

$$L \propto v_s^3 \propto t^{-3\alpha}, \tag{9}$$

which can be expressed in magnitude units as

$$m_{\text{ejecta-CSM}} = C - \frac{5}{2}\log_{10} t^{-3\alpha} = C + \frac{15}{2}\alpha \log_{10} t, \tag{10}$$

where C is a constant that incorporates $\dot{M}$, ρ_{SN}, v_w, n, and the appropriate units for those parameters. The difference in magnitude between two times, t_1 and t_2, then becomes

$$m_{t_2} - m_{t_1} = \frac{15}{2}\alpha \log_{10} \frac{t_2}{t_1}. \tag{11}$$

We obtain a date of B-maximum for the supernova component of 2452606 JD from our SN Ia-light curve analysis. Our fit yields an $\alpha = 0.16 \Rightarrow n = 8.5$ for any fixed $\dot{M}$ and v_w. This n is squarely in the range of values suggested by Chevalier & Fransson (1994) as being typical for SN ejecta. While Chevalier & Fransson (1994) is framed in the context of SNe II, their formalism applies to any SN explosion into a surrounding medium whose ejecta density profile is described by their analytic model.

The interaction scaling relations presented above are useful for decomposing the interaction and supernova contributions to the total light curve of SN 2002ic. This simple, analytic description approximates our data reasonably well. However, more sophisticated theoretical calculations, which are beyond the scope of this paper, are necessary to more quantitatively derive the detailed physical parameters of the SN ejecta and the CSM (see Chugai & Yungelson (2004)).

6. Discussion

6.1. Inferred CSM structure and Progenitor Mass-Loss History

We can match the inferred SN ejecta-CSM component of Hamuy et al. (2003) with the interaction model described above and reproduce the light curve near maximum light by adding the flux from a normal SN Ia. Fig. 3 shows our model fit in comparison with the observed light curve of SN 2002ic. Note that our model does not match the observed bump at 40 days after maximum.

Hamuy et al. (2003) note a similar disagreement, but the data we present here show that this region is clearly a second bump rather than just a very slow decline. This discrepancy could be

explained by a change in the density of the circumstellar medium due to a change in the progenitor mass-loss evolution at that point. In fact, our simple fit is too bright before the bump and too dim during the bump, implying more structure in the underlying CSM than accounted for in our model. Any clumpiness in the progenitor wind would have to be on the largest angular scale to create such a bump and would not explain the new decline rate shown by our observations to extend out to late time . We find that our data are consistent with a model comprising three CSM density regions: (i) an evacuated region out to $20v_s$ days; (ii) CSM material at a nominal density ($\rho \propto r^{-2}$) out to $\sim 100v_s$ days; and (iii) an increase in CSM density at $\sim 100v_s$ days, with a subsequent r^{-2} fall-off extending through the $800v_s$ days covered by our observations. This model agrees well with the light curve of SN 2002ic, but, as it involves too many parameters to result in a unique fit using only the photometric data, we do not show it here.

Our data, particularly the pre-maximum observations, provide key constraints on the nature of the progenitor system of SN 2002ic. In the context of our model, a mass-loss gradient of some form is required by our early data points. As a computational convenience, our model assumes that the transition to a nominal circumstellar density is described by $\sin(\frac{t}{20\ \mathrm{days}})$. If the mass-loss rate had been constant until just prior to the explosion, then the $t^{-3\alpha}$ model light curve would continue to curve upward and significantly violate our first data point at the 7σ level (as shown by the line extended from the ejecta-CSM component in Fig. 3). If the conversion of kinetic energy to luminosity is immediate and roughly constant in time, as assumed in our model, we would conclude that a low-density region must have existed between the star and 20 days$\cdot v_s$ out from the star. For example, as a stellar system transitions from an AGB star to a proto-planetary nebula (PPN), it changes from emitting a denser, cooler wind, to a hotter, less dense wind (Kwok 1993). This hot wind pushes the older wind out farther and creates a sharp density gradient and possible clumping near the interface between the cool and hot winds (Young et al. 1992). This overall structure is similar to that which we infer from our modeling of SN 2002ic. Assuming a SN ejecta speed of $v_s = 30,000$ km s^{-1} and a progenitor star hot wind speed of $v_w = 100$ km s^{-1} (Young et al. 1992; Herpin et al. 2002), we conclude that the hot wind must have begun just ~ 15 years prior to the SN explosion. Alternatively, there is also the possibility that the conversion from kinetic energy to optical luminosity is for some reason significantly less efficient at very early times.

It is interesting to note that the observed light curve decline rate of SN 2002ic after 40 days past maximum light is apparently constant during these observations. Spectroscopic study (Wang et al. 2004) shows the highest observed velocity of the ejecta to be around 11000 km s^{-1} at day 200 after maximum light. If we assume a constant expansion rate, these observations of continuing emission through ~ 320 days after maximum provide a lower limit of $\sim 3 \times 10^{16}$ cm for the spatial extent of the CSM. Compared to a nominal pre-explosion stellar wind speed of 10 km s^{-1}, the ejecta is moving ~ 1000 times more rapidly and thus has overtaken the progenitor wind from the past ~ 800 years. The overall smoothness of the late-time light curve shows the radial density profile of

the CSM to be similarly smooth and thus implies a fairly uniform mass-loss rate between 100–800 years prior to the SN explosion.

We take the lack of enhanced flux at early times and the bump after maximum light as evidence for a gap between the SN progenitor and the dense CSM as well as a significant further change in the mass-loss of the progenitor system ~ 100 years prior to the SN explosion.

6.2. Reinterpretation of Past SNe IIn

These new results prompt a reexamination of supernovae previously classified as Type IIn, specifically SN 1988Z (Pollas et al. 1988; Stathakis & Sadler 1991), SN 1997cy (Sabine et al. 1997; Turatto et al. 2000; Germany et al. 2000), and SN 1999E (Cappellaro et al. 1999; Siloti et al. 2000; Rigon et al. 2003). These supernovae bear striking similarities in their light curves and their late-time spectra to SN 2002ic. However, SN 2002ic is the only one of these supernovae to have been observed early in its evolution. If SN 2002ic had been observed at the later times typical of the observations of these Type IIn SNe, it would not have been identified as a Type Ia. It is interesting to note that Chugai & Danziger (1994) found from models of light curves of SN 1988Z that the mass of the SN 1988Z supernova ejecta is on the order of 1 $M_{\odot}$, which is consistent with a SN Ia.

We next explore the possibility that SN 1997cy and SN 1999E (a close parallel to SN 1997cy) may have been systems like SN 2002ic. Hamuy et al. (2003) found that available spectra of SN 1997cy were very similar to post-maximum spectra of SN 2002ic. We complement this spectroscopic similarity with a comparison of the photometric behavior of SN 1997cy and SN 2002ic. As shown in Fig. 4, the late-time behavior of both SNe appear remarkably similar with both SNe fading by ~ 2.5 magnitudes 8 months after their respective discoveries. The luminosity decay rate of the ejecta-CSM interaction is directly related to the assumed functional form for the ejecta density and the mass-loss rate (Eq. 1). The observed late-time light curves of SN 1997cy and SN 1999E clearly follow a linear magnitude decay with time, which implies an exponential flux vs. time dependence: $m \propto t \Rightarrow \text{flux} \propto e^{Ct}$. If the ejecta density followed an exponential rather than a power-law decay, the magnitude would similarly follow a linear magnitude-time decay. Fig. 5 shows a fit to the light curve of SN 2002ic using the framework of Sec. 5 but using an exponential SN-ejecta density profile. Chevalier & Fransson (2001) suggest that SNe Ia follow exponential ejecta profiles (Dwarkadas & Chevalier 1998) while core-collapse SNe follow power-law decays (Chevalier & Soker 1989; Matzner & McKee 1999). Thus, if SN 1997cy and SN 1999E had been core-collapse events, they would have been expected to show power-law declines. Instead, their decline behavior lends further credence to the idea that they were SN Ia events rather than core-collapse SNe. Although we modeled the light curve of SN 2002ic using a power-law

ejecta profile, SN 2002ic was not observed between 100 and 200 days after explosion, so its decay behavior during that time is not well constrained. Its late-time light curve is consistent with the linear magnitude behavior of SN 1997cy. We fit such a profile to our data (see Fig. 5 & 6) and arrive at an exponential fit to the flux of the form $e^{-0.003t}$ where t is measured in days. As the solution for the SN-ejecta interaction is not analytic, we cannot immediately relate the exponential decay parameter to any particular property of the SN ejecta. Taken together in the context of the Chevalier & Fransson (1994) model, SN 2002ic, SN 1997cy, and SN 1999E lend support to numerical simulations of the density profiles of SNe Ia explosions.

If we take the time of maximum for SN 1997cy to be the earliest light curve point from Germany et al. (2000) and shift the magnitudes from the redshift of SN 1997cy, $z = 0.063$ (Germany et al. 2000), to the redshift of SN 2002ic ($z = 0.0666$), we find that the luminosity of both SNe agree remarkably well. This further supports that hypothesis that SN 1997cy and SN 2002ic are related events. However, we note that the explosion date of SN 1997cy is uncertain and may have been 2–3 months prior to the discovery date (Germany et al. 2000; Turatto et al. 2000).

Fig. 3 & 5 show that neither a power-law nor an exponential model allow for a significant ejecta-CSM contribution before maximum light. In each figure, the "[exp] ejecta-CSM fit w/o gap" line shows how the SN ejecta-CSM interaction would continue if the density profile remained the same. Both lines significantly disagree with the earliest light curve point. This is consistent with our earlier conclusion that the light curve is dominated by the SN until near maximum light.

6.3. Relation to Proto-Planetary Nebulae?

The massive CSM and spatial extent inferred for SN 2002ic are surprisingly similar to certain PPNe and the atmospheres of very late red giant stars evolving to PPNe. Such structures are normally short-lived (less than or on the order of 1000 years). The polarization seen by Wang et al. (2004) suggests the presence of a disk-like structure surrounding SN 2002ic. Furthermore, the Hα luminosity and mass and size estimates suggest a clumpy medium. Combined with the evidence presented here for a possible transition region between a slow and fast wind, we are left with an object very similar to observed PPNe. We encourage more detailed radiative hydrodynamic modeling of SNe Ia in a surrounding medium as our data provide valuable constraints on this important early-time phase.

Of particular interest are bi-polar PPNe where a WD companion emits a fast wind that shapes the AGB star wind while simultaneously accreting (Soker & Rappaport 2000) mass from the AGB star.

Typical thermonuclear supernovae are believed to have accretion time scales of 10^7 years, yet

several SNe Ia (SN 2002ic and possibly SN 1988Z, SN 1997cy, and SN 1999E) out of several hundred have been observed to show evidence for significant CSM. If the presence of a detectable CSM is taken as evidence that these SNe exploded within a particular ~ 1000 year-period in their respective evolution, such as the PPN phase, this coincidence would imply a factor of ~ 100 enhancement (10^7 years $/1000$ years $/100$) in the supernova explosion rate during this period. Thus we suggest that it is not a coincidence that the supernova explosion is triggered during this phase.

7. Conclusions

The supernova 2002ic exhibits the light curve behavior and hydrogen emission of a Type IIn supernova after maximum but was spectroscopically identified as a Type Ia supernova near maximum light. The additional emission is attributed to a contribution from surrounding CSM. This emission remains quite significant ∼11 months after the explosion. The discovery of dense CSM surrounding a Type Ia supernova strongly favors the binary nature of Type Ia progenitor systems to explain the simultaneous presence of at least one degenerate object and substantial material presumably ejected by a significant stellar wind. However, it is as yet unclear whether the available data for SN 2002ic can prove or disprove either the single- or the double-degenerate scenario, although the inferred resemblance to PPN systems is suggestive. The early-time light curve data presented in this paper strongly suggest the existence of a $\sim 15\ (\frac{v_w}{10\ \mathrm{km/s}})^{-1}$ year gap between the exploding object and the surrounding CSM. Our discovery and early- through late-time photometric followup of SN 2002ic suggests a reinterpretation of some Type IIn events as Type Ia thermonuclear explosions shrouded by a substantial layer of circumstellar material.

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Table 1. The unfiltered magnitudes for SN 2002ic as observed by the NEAT telescopes and shown in Fig. 1. The left brackets ([) denote limiting magnitudes at a signal-to-noise of 3. A systematic uncertainty of 0.4 magnitudes in the overall calibration is not included in the tabulated uncertainties. (See Sec. 2 for further discussion of our calibration).

JD - 2452000	E Mag	E Mag Uncertainty		Telescope
195.4999	[20.52			Palomar 1.2-m
224.2479	[20.44			Palomar 1.2-m
250.2492	[21.01			Palomar 1.2-m
577.4982	[20.29			Haleakala 1.2-m
591.2465	19.04	− 0.07	+ 0.07	Palomar 1.2-m
598.2519	18.20	− 0.06	+ 0.06	Palomar 1.2-m
599.3306	18.11	− 0.03	+ 0.03	Palomar 1.2-m
628.0956	18.12	− 0.03	+ 0.03	Palomar 1.2-m
656.2508	18.06	− 0.13	+ 0.12	Haleakala 1.2-m
674.2524	18.47	− 0.13	+ 0.12	Haleakala 1.2-m
680.2519	18.53	− 0.10	+ 0.09	Haleakala 1.2-m
849.5003	[18.88			Haleakala 1.2-m
853.4994	[18.54			Haleakala 1.2-m
855.4963	[19.32			Haleakala 1.2-m
858.4986	[19.23			Haleakala 1.2-m
860.4992	[18.74			Haleakala 1.2-m
864.5017	[17.17			Haleakala 1.2-m
874.4982	19.05	− 0.15	+ 0.13	Haleakala 1.2-m
876.4998	19.15	− 0.10	+ 0.09	Haleakala 1.2-m
902.4989	19.29	− 0.07	+ 0.07	Palomar 1.2-m
903.4138	19.47	− 0.08	+ 0.08	Palomar 1.2-m
932.2942	19.42	− 0.10	+ 0.09	Palomar 1.2-m

Table 2. The V-band magnitudes for SN 2002ic as synthesized from the VLT spectrophotometry of Wang et al. (2004) and shown in Fig. 2.

JD - 2452000	V Mag	V Mag Uncertainty
829	19.05	± 0.05
850	19.22	± 0.05
852	19.15	± 0.10
912	19.30	± 0.05

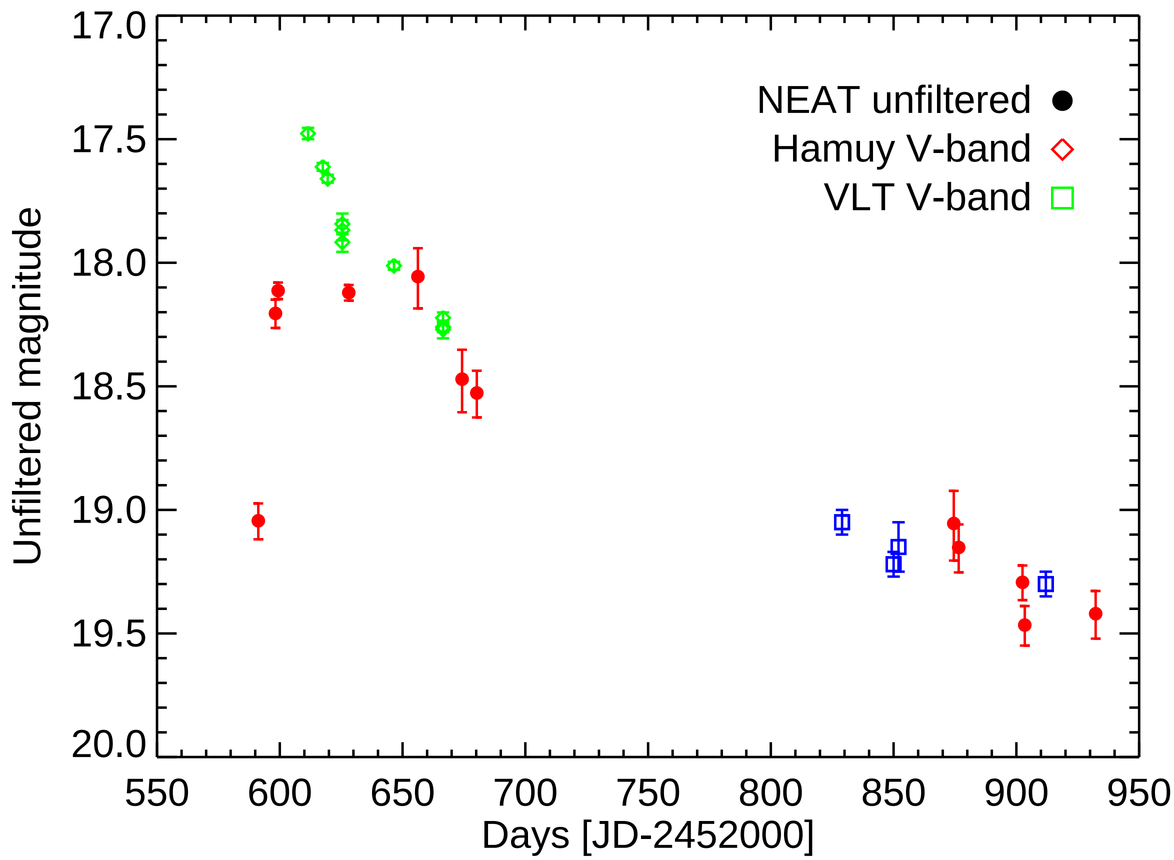

Fig. 1.— The unfiltered optical light curve of SN 2002ic as observed by NEAT with the Palomar 1.2-m and Haleakala 1.2-m telescopes (see Table 1). The magnitudes have been calibrated against the USNO-A1.0 POSS-E stars in the surrounding field. No color correction has been applied. Also shown are the observed V-band magnitudes from Hamuy et al. (2003) and V-band magnitudes from the spectrophotometry of Wang et al. (2004).

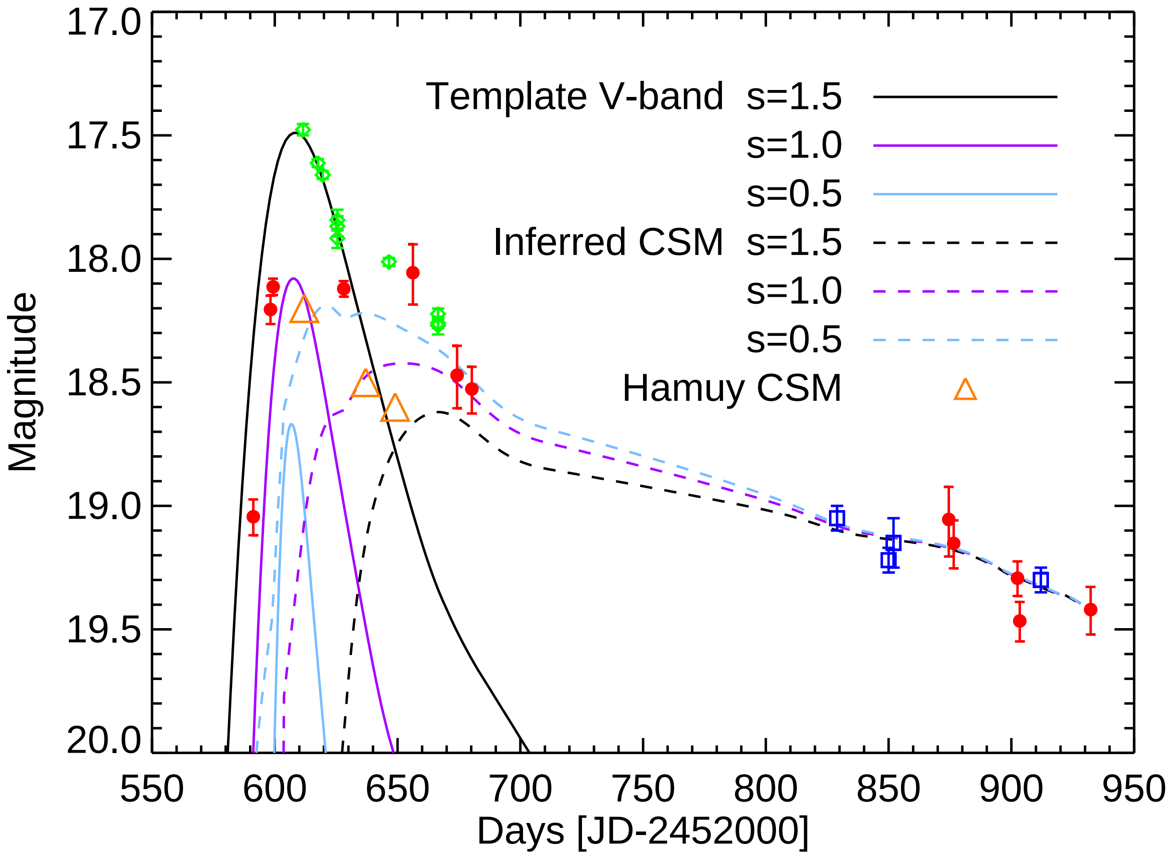

Fig. 2.— A template SN Ia V-band light curve (solid lines – stretch decreases from top to bottom line) shown for comparison with the photometric observations at several stretch values, s, where the magnitude-stretch relation $\Delta m = 1.18\,(1 - s)$ has been applied. The difference between the observed photometry points and the template fit has been smoothed over a 50-day window (dashed lines). Note that an assumption of no CSM contribution in the first 15 days after maximum light (i.e. $s = 1.5$) is in conflict with the spectroscopic measurements of Hamuy et al. (2003) (open triangles–no error bars available).

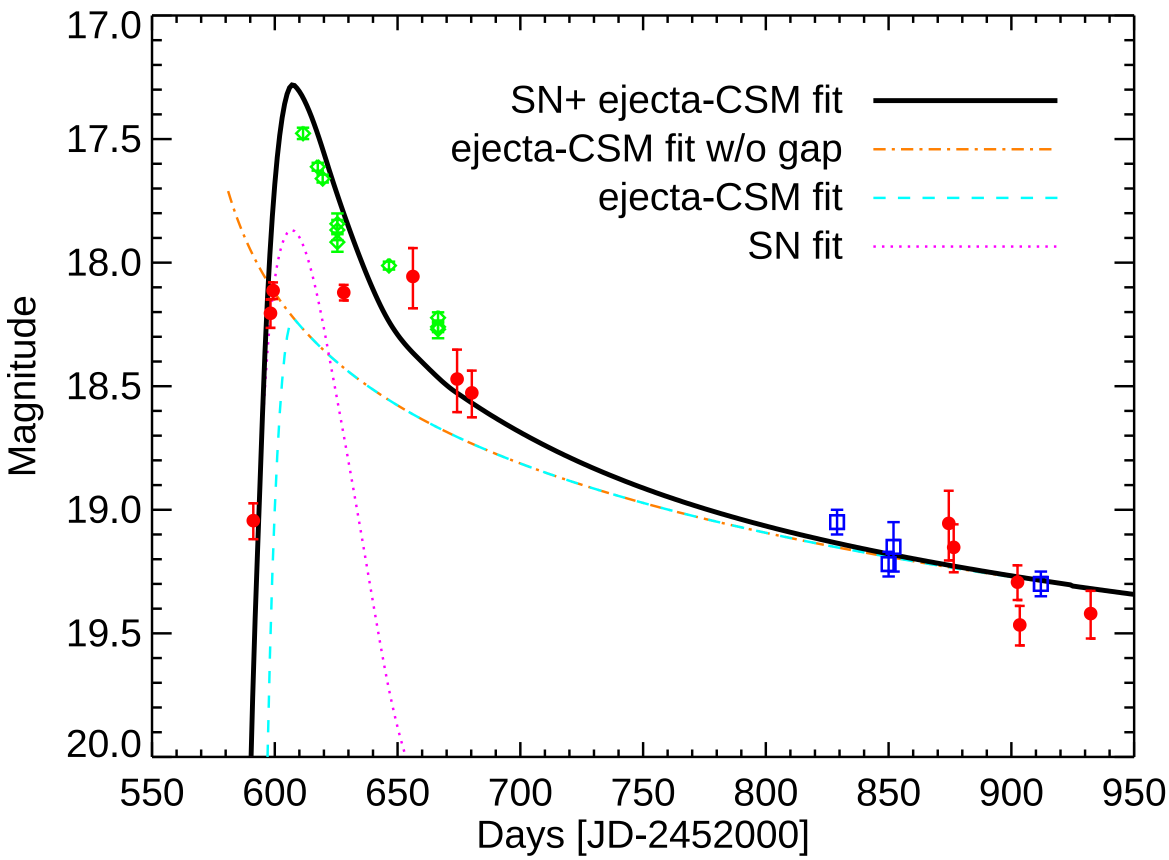

Fig. 3.— The observed photometry compared with the SN + power-law ejecta-CSM model described in Sec. 5.

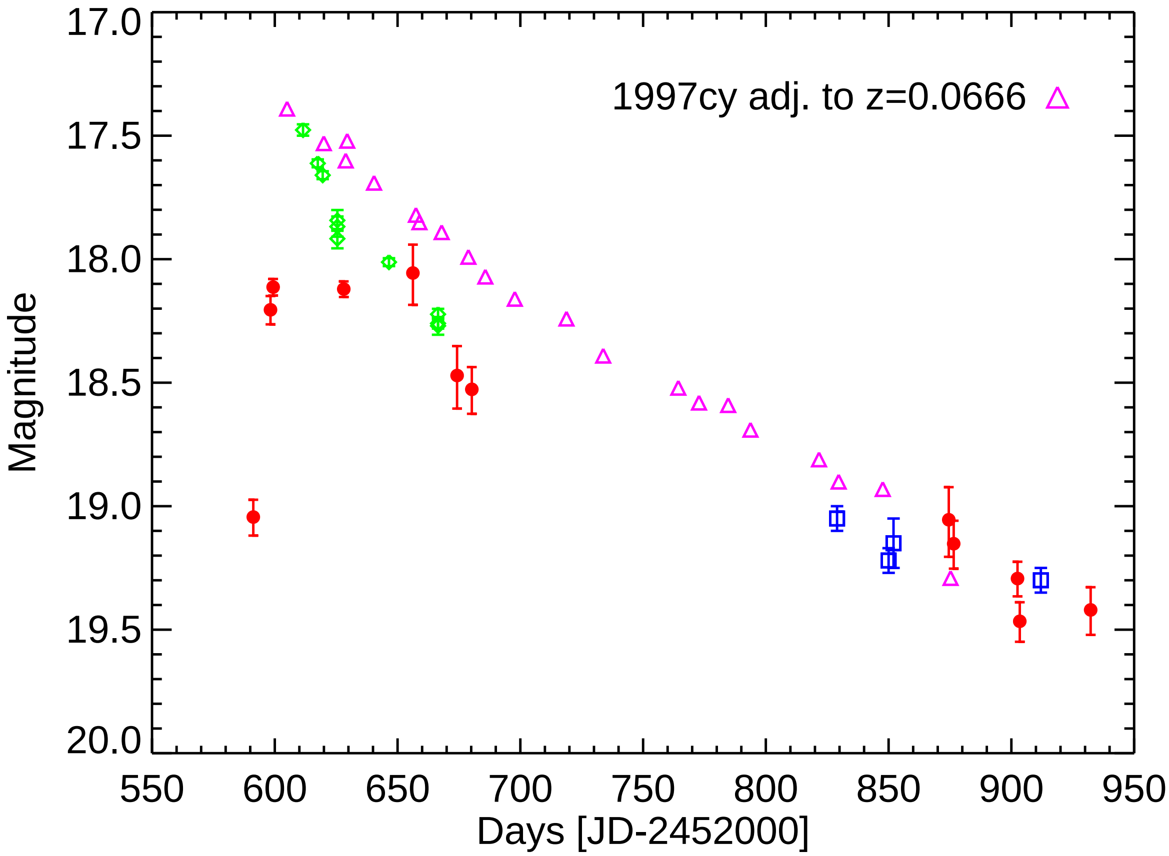

Fig. 4.— The NEAT unfiltered and Hamuy V-band observations of SN 2002ic compared to the K-corrected V-band observations of SN 1997cy from Germany et al. (2000). No date of maximum or magnitude uncertainties are available for SN 1997cy. Here the maximum observed magnitude for SN 1997cy has been adjusted to the redshift of 2002ic, z=0.0666 (Hamuy et al. 2003), and the date of the first light curve point of SN 1997cy has been set to the date of maximum for SN 2002ic from our V-band fit.

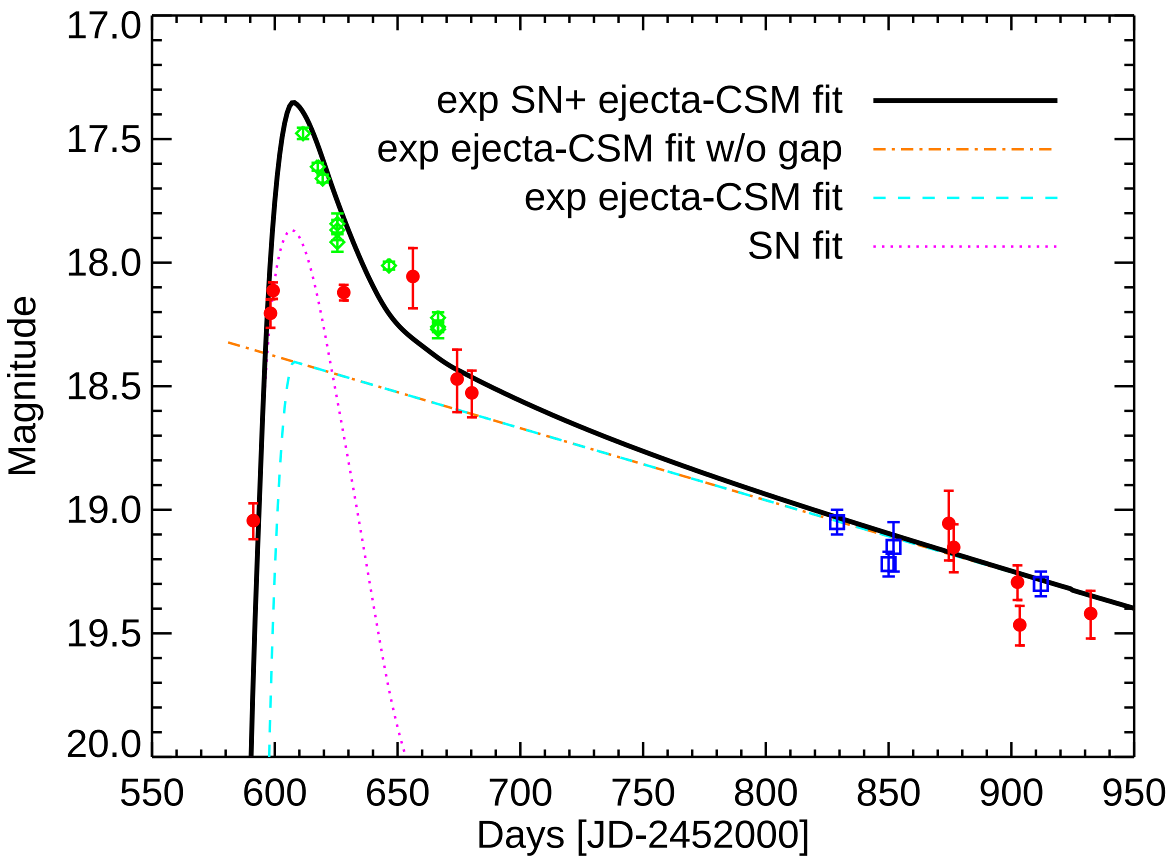

Fig. 5.— The observed photometry compared with the SN + exponential ejecta-CSM model described in Sec. 6.

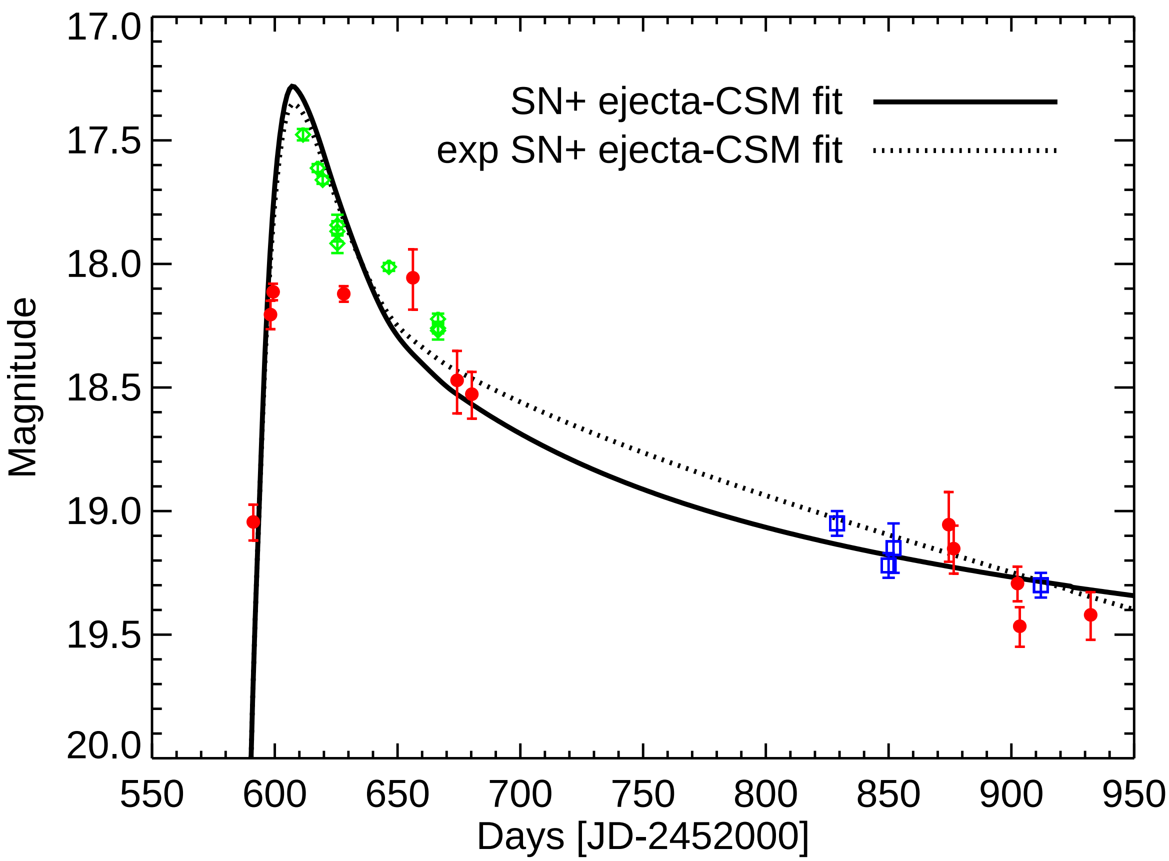

Fig. 6.— A comparison of fits with power-law (solid) and exponential (dotted) SN ejecta density profiles.

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